# Efficient input and output coupling between planar photonic crystal waveguides and fiber tapers

**Paul E. Barclay, Kartik Srinivasan, Matthew Borselli, and Oskar Painter**
*Department of Applied Physics, California Institute of Technology, Pasadena, CA 91125, USA.*
*phone: (626) 395-6269, fax: (626) 795-7258, e-mail: pbarclay@caltech.edu*

**Abstract:** Highly efficient (> 94%) contradirectional coupling into and out of a photonic crystal waveguide is measured using a fiber taper probe as both a source and a collector.

**OCIS codes:** (060.1810) Couplers, switches, and multiplexers; (130.3120) Integrated optics devices

A requirement for the practical demonstration of photonic crystal (PC) devices is the ability to efficiently couple light into and out of them. Fiber tapers [1], used as optical probes, allow highly efficient evanescent coupling [2] between photonic crystal waveguides (PCWGs) and fiber optics [3]. In addition to its high efficiency, two attractive features of this coupling scheme are its mode selective nature and wafer-scale geometry, which we have exploited to measure the spatial and dispersive properties of PCWG modes [4]. Here we study the fiber-PCWG-fiber coupling efficiency of this technique by measuring light which is coupled contradirectionally from a fiber taper into a PCWG and recollected by the backwards propagating fiber taper mode [5], and show that the coupling efficiency is > 94%. We then discuss the implementation of an efficient PCWG-PC cavity probe.

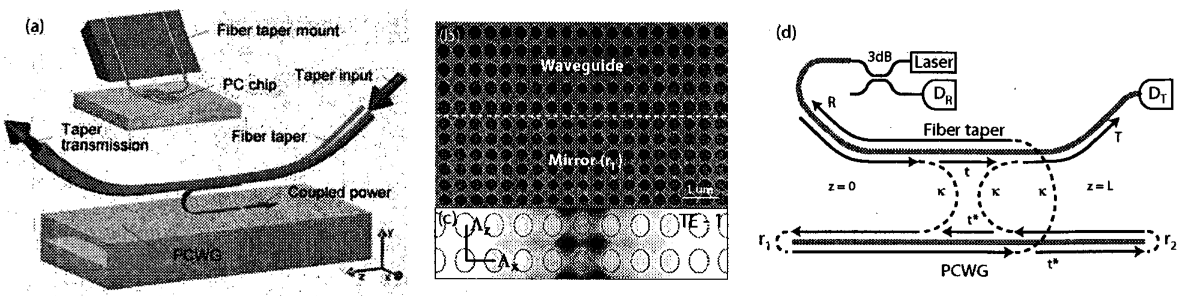


Fig. 1. (a) Schematic of the coupling scheme. (b) Field profile of the TE-1 mode studied here. (c) SEM of the PCWG and termination. (d) Illustration of the experimental apparatus and the contradirectional coupling process.

In order to directly measure the efficiency of this coupling scheme (shown in Fig. 1(a)), we designed a PCWG that allows light which is coupled into it to be recollected by the backward propagating fiber taper mode. The PCWG was formed by a graded defect in a compressed square lattice of air holes in a silicon membrane; a typical fabricated PCWG is shown in Fig. 1(b), and the mode studied here (labeled TE-1) is shown in Fig. 1(c). A highly reflective waveguide termination (labeled by $r_1$) was realized by removing the lattice compression, resulting in a partial bandgap as seen by the TE-1 mode. On the opposite end of the PCWG, a poor reflector ($r_2$) was realized by gradually removing the defect defining the PCWG. As illustrated by Fig. 1(d), by measuring the signals $T$ transmitted through the fiber taper and $R$ coupled into the backward propagating fiber mode, the coupling efficiency $|\kappa|^2$ of this technique can be characterized.

Figure 2(a) shows measured $T$ and $R$ as a function of wavelength ($\lambda$) when a fiber taper ($\sim 2\ \mu$m diameter) is positioned 200 nm above the PCWG. At $\lambda = 1600$ nm the fundamental fiber taper mode and TE-1 PCWG mode are phase matched, resulting in a resonant decrease in $T$ and increase in $R$ over a $\sim 20$ nm bandwidth. Figure 2(b) shows the on-resonance values of $T$ and $R$ as a function of taper height, as well as theoretical fits. Assuming that multiple reflections within the PCWG can be neglected, the maximum measured reflected signal, $R_{\max} = 0.88$, can be used to place a lower bound on the coupling efficiency. This value is a measure of light which is coupled into the PCWG, reflected at $r_1$, and coupled back into the fiber taper; it suggests a coupling efficiency $|\kappa|^2 \geq \sqrt{R_{\max}}/|r_1| > 0.94$. A more detailed analysis in Ref. [5] of the dependence of $T$ and $R$ on taper height confirms this intuitive calculation.

These results promise to allow efficient probing of future integrated PC devices. Of particular interest is efficient loading of high-Q PC cavities. Figure 2(c) shows a schematic illustrating a scheme for integrating the PCWG used

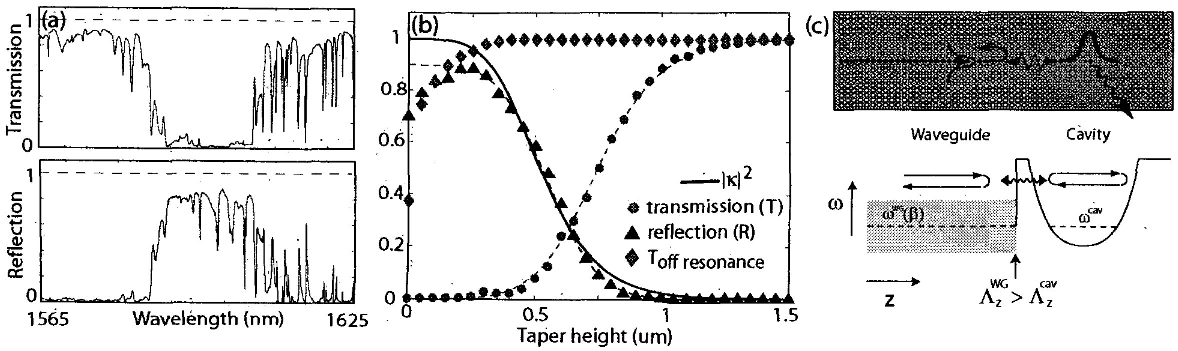


Fig. 2. (a) Transmission (top) and reflection (bottom) of the fiber taper as function of wavelength for a taper height of 200 nm. (b) Measured taper transmission minimum, reflection maximum, and off resonant transmission as a function of taper height. In (a-b) Data is normalized to the taper transmission in absence of the PCWG. (c) Schematic of scheme for integrating the PCWG studied here with a suitable high-Q cavity.

here with a recently demonstrated [6] high-Q (40 000) cavity mode, which is expected to couple preferentially to the TE-1 PCWG mode. By replacing the mirror $r_1$ in the experiments presented above with the cavity studied Ref. [6], an efficient *fiber taper-PCWG-PC cavity* probe can be realized.

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